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INTRODUCTION

The Mirror Fusion Test Facility (MFTF) currently under construction at the Lawrence Livermore Laboratory includes a Sustaining Neutral Beam Power Supply System (SNBPSS) consisting of 24 power-supply sets. The System will operate in long pulses (initially .5 seconds and eventually 30 seconds) at high power (200 MW), which will necessitate a large source of ac power. To meet this requirement, a new 230-kV substation is also being built at LLL.** The constraints of cost, equipment protection, short operating lifetime (10 years), and reliability dictated a unique substation design. Its unusual features include provisions for fast fault detection and tripping, a capability for limiting ground fault current, low impedance, and economical design.

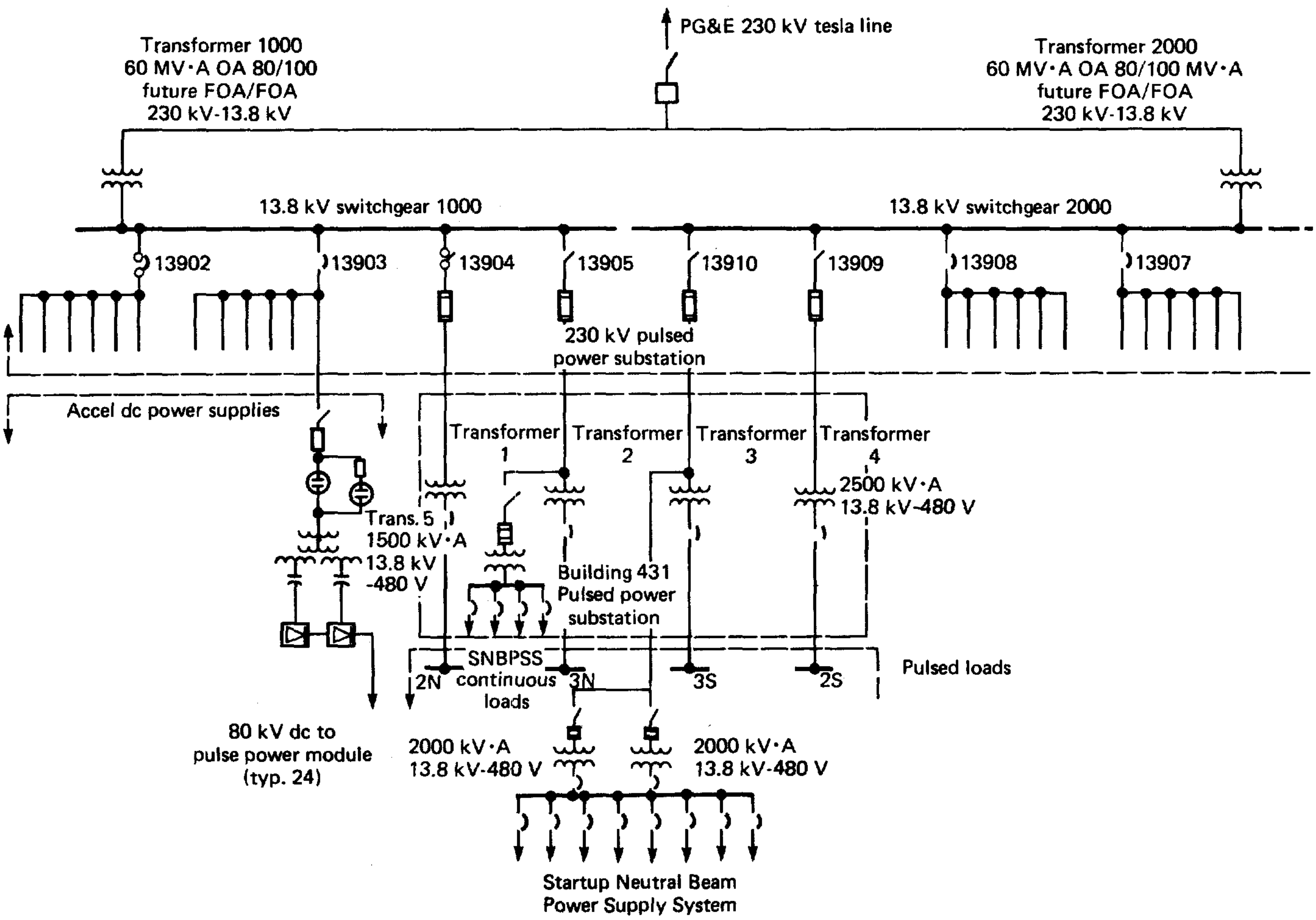

Fig. 1 Lawrence Livermore Laboratory MFTF Pulsed AC Power System

*Work performed under tha auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under contract number W-7405-ENG-48.

**The architecture/engineering firm of Daniel, Mann, Johnson, and Mendenhall (DMJM), Figure 2, was retained to provide engineering, design, and drawing specification preparation for the substation. The construction contractor is Scott-Buttner Corporation of Oakland, CA.

Load Requirements of the Power Supply System

The total load of the SNBPSS is 225 MVA for 30 seconds in a pulse every 5 minutes. The Accel DC Power Supply (ADCPS) is 212 MVA load (supplied at 13.8 kV) and the rest of the SNBPSS presents a load of 13 MVA (supplied at 480 V). In addition, a Startup Neutral Beam Power Supply System receives 5200 kVA of 480-volt power in a 5-seconds-on 5-min-off duty cycle. The total load is thus 230 MVA for 5 seconds and 225 MVA for the next 25 seconds, with the 30-second duty cycle repeated at 5 minute intervals. The MFTF Pulsed AC Power System single line diagram is shown as Figure 1.

MFTF Pulsed ac Power System

To meet the large ac power requirements for this system, the substation will receive the power from a new PG & E 230-kV transmission line and step it down to 13.8 kV. Figure 2 shows the electrical arrangement of the substation.

Switchgear 230 kV

The 230 kV switchgear is an S&C, Inc., Circuit Switcher. Ratings of the circuit switcher are:

Nominal voltage, kV	230
Maximum voltage, kV	242
Continuous current, A rms	1,600
Three-second current, A rms	43,750
Momentary current, A rms	80,000
Fault closing current, A crest	40,000
Interrupting current, A rms	
Primary	8,000
Secondary	6,000
Basic Impulse Level (BIL), kV	900

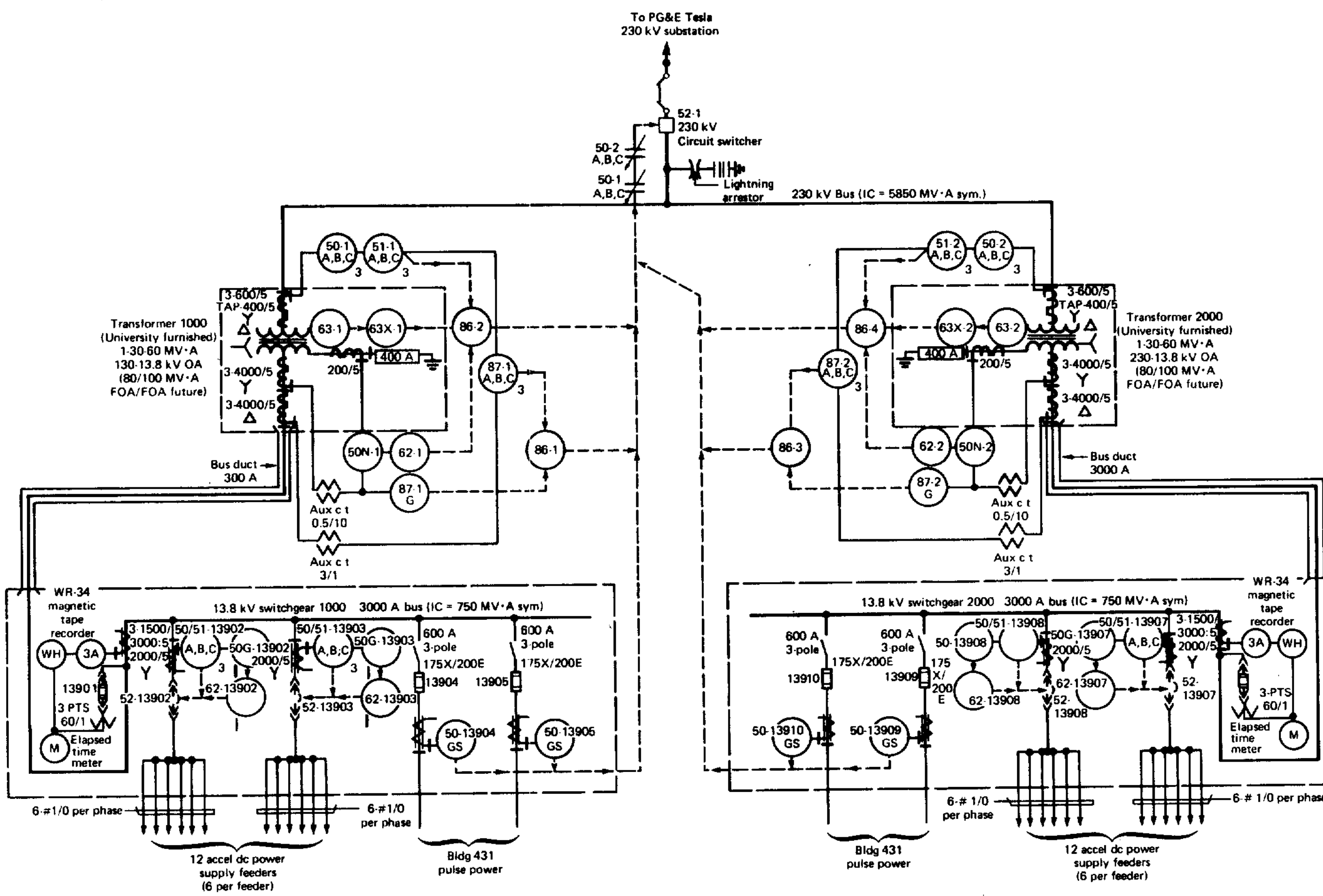

Fig. 2 Electrical Arrangement of the 230-kV Pulsed Power Substation

Lightning Arresters

The design includes 192 kV GE Tranquell lightning arresters. Note that one set of lightning arresters is used to protect both 230 kV transformers. This is not the common practice, but there are two reasons for it in this case. First, lightning strokes are very rare in the Livermore Valley. Also, it is expected that most lightning pulses or switching surges will arrive via the 230 kV transmission line, since it is exposed for a long distance. Second, the substation is provided with a lightning-shield wire assembly suspended by four 45-foot towers (two of which are part of the 230-kV takeoff structure).

Stepdown Transformers

The substation's most important components are two Westinghouse 230-kV to 13.8-kV Δ-Y stepdown transformers. Each of these transformers is rated 60 MVA OA (self-cooled) continuous and can be loaded to approximately a 120 MVA peak. The transformers were specified for pulse loading at the levels given above and also for 60 MVA continuous loading in case the Laboratory has future use for the transformers. The continuous rating should also enhance their value as used apparatus when the MFTF experiment is concluded. For the same reasons, the transformers were built with provisions for future forced-air forced-oil cooling. The high-voltage winding BIL is 750 kV, with bushing BIL of 900 kV.

Metal-clad Switchgear

Each stepdown transformer feeds a metal-clad, 13.8-kV switchgear assembly consisting of a metering compartment, two 13.8-kV circuit breakers, and two 13.8-kV load-interrupter switches. Insofar as possible, all protective and control devices are mounted in the switchgear assembly. Ratings of the switchgear devices are:

Nominal voltage, kV	13.8
Bus current, A	3000
Nominal 3-phase MVA class	750
BIL, kV	95
Breakers current, amp	2000
Load Interrupter Switch current, A	600
Fuse rating	175E/200X

Impedance and Voltage Requirements

Because proper performance of the accel dc power supplies requires low impedance of the 13.8-kV system, its short-circuit-current level was the limiting factor in the choice of transformer impedances. The current rating of 600-A load-interrupter switches is 40,000-A asymmetrical-fault current. At the range of voltages which will appear in the 13.8-kV system, the ratings of the 750-MVA circuit breakers are 29,800 amperes interrupting and 58,000 amperes rms momentary. The transformer impedance was chosen and the fault current calculated in accordance with ANSI C37.010.[1]

The voltage in the PG & E 230-kV system could vary from 225 to 235 kV. Because of PG & E's power-factor correction requirements, voltage regulation is not a problem in this substation. The ADCPS load is overcompensated for power-factor correction to maintain unity power function at the 230 kV terminals and is, therefore, a source of reactive power. Computer anaylsis (by SRI, Inc., performed under subcontract to Aydin, the supplier of the power supply system) shows a voltage rise of approximately 2% when all 24 accel power supplies are turned on to their full load value.

Operation Controls

All controls for operating the substation are mounted on the 13.8-kV switchgear assemblies and allow a local operator to place the substation in service or take it out of service. However, there are alarms in the MFTF control room to indicate relay trips and high transformer temperatures. PG & E requires that kilowatt-hour pulses and analog kilowatt-hour signals be telemetered to its dispatch center in San Francisco. In addition, the telephone lines leased for this purpose include a voice communication link between the MFTF operator and the PG & E load dispatcher, and an alarm channel through which PG & E can alert the MFTF operator and computer to any problem requiring MFTF to shut down.

Fault Protection

Because of the high cost and long repair time for the substation components, as well as the hazard to personnel caused by the high energy available in a short circuit, considerable effort was put into the design and coordination of the protective equipment. Protective equipment, in this case, means fault detection equipment (protective relays) and interrupting equipment (circuit breakers, fuses, and circuit switchers).

Transformers

All transformer protective devices trip through four lockout relays. Lockout relays 86-1 and 86-2 are for primary and backup protection, respectively, of transformer no. 1000, and lockout relays 86-3 and 86-4 provide primary and backup protection, respectively, for transformer 2000. The primary-lockout relays are tripped by the transformer-differential relays and ground-differential relays. The backup-lockout relays are tripped by the transformer's primary time-overcurrent relay and its neutral instantaneous-overcurrent relay. Note that the transformer's neutral-overcurrent relay trips via a time-delay relay, which allows time for the feeder ground-fault relaying to trip first in the event of a feeder ground fault. The transformer's sudden-pressure relay also trips the backup-lockout relay. All four lockout relays trip the 230-kV circuit switcher. In each transformer primary circuit, instantaneous-overcurrent relays are provided. These relays block tripping of the S & C 230-kV Circuit-Switcher in the event of a fault of such high magnitude that it would exceed the rating of the circuit switcher; for example, a phase-to-phase fault in the primary winding or a bushing-to-bushing fault in the transformer.

Accel DC Power Supply

For the breakers feeding the ADCPS, the primary protective devices are instantaneous-and-time-overcurrent relays for phase fault protection, and

[1]American National Standards Institute, Application Guide for ac High-Voltage Circuit Breakers Rated on a Symmetrical-Current Basis, Publication No. C37.010-1972.

neutral-overcurrent relays tripping through timing relays for ground-fault protection. The timing relays are provided because each ADCPS includes an instantaneous ground-detection relay. The timers ensure that the relay in the ADCPS has a chance to trip for faults therein. The feeder relays are backed up by the transformer's primary phase overcurrent and neutral-overcurrent relays. Fig. 3 shows the breakers and relay time-current coordination for the ADCPS Feeders.

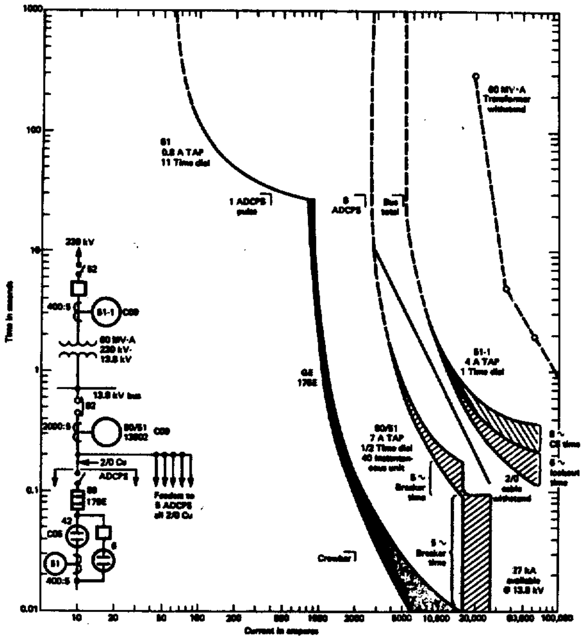

Fig. 3 ADCPS Feeder Coordination

Feeders to 480-V Stepdown Transformers

Phase-fault protection for the four load-interrupter switches which feed the stepdown (13.8 kV to 480 volt) transformers is provided by current-limiting power fuses. Protection from ground faults is provided by instantaneous ground-detection relays. Because the load-interrupter switches are too slow to be protective devices, the ground-detection relays trip the 230-kV circuit switcher. This does involve a loss of selectivity in that it trips more of the substation than necessary, but the alternative would have been to use circuit breakers for these two relatively lightly-loaded feeders, at a cost approximately ten times that of the load-interrupter switches. The transformer feeders' fuses and ground-detection relays are backed up by the 60-MVA transformer's primary time-overcurrent and neutral-overcurrent relays. Figs. 4 and 5 show the time-current coordination for these feeders.

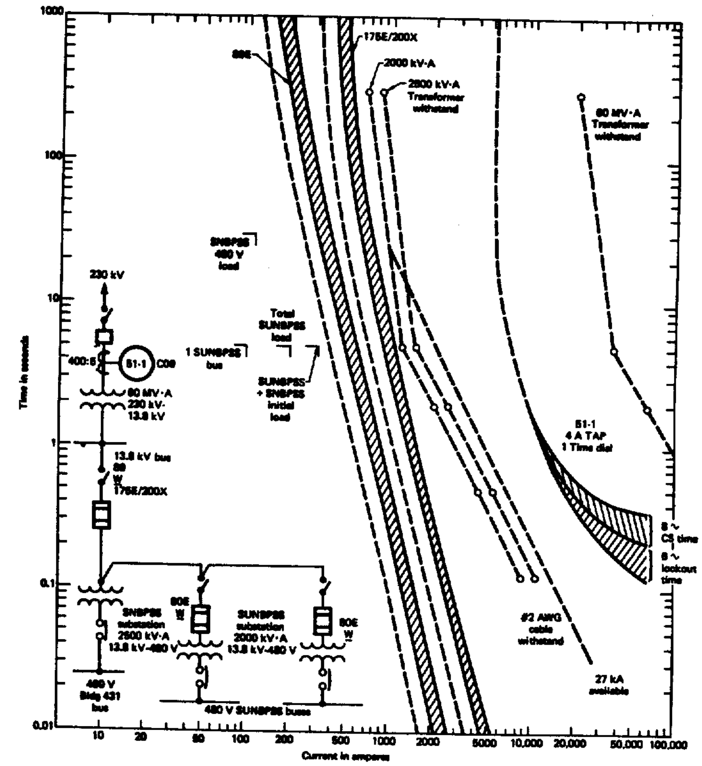

Fig. 4 Unit Substation Feeder Coordination

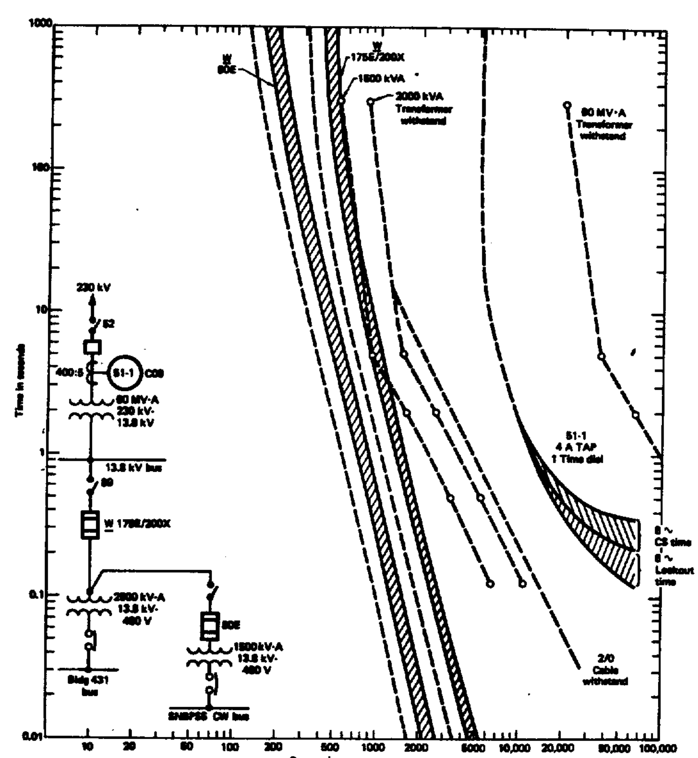

Fig. 5 Unit Substation Feeder Coordination

PG & E Revenue Metering

A watt hour meter, a magnetic tape recorder for demand metering, and telemetering equipment will be provided by PG & E along with associated potential and current transformers. In addition, an elapsed-time meter (shown on the single line diagram) will be used by PG & E to bill for the transformer's no-load losses.

Environmental and Physical Requirements

Figure 6 shows the substation layout. The objectives of this layout were twofold; flexibility and compactness to minimize costs of buses and raceways and to conserve Laboratory real estate. Two main options in the design are, first, that room was allowed in the primary buswork feeding each transformer for individual circuit switchers and second, that room was provided for a third possible future transformer and switchgear assembly.

Weather and Seismic Stresses

The Livermore site is a fairly severe environment for several reasons. Ambient temperatures are often very high, with 110°F during the summer day being reasonably common. The site is in a very dusty area and the wide temperature variations from daytime high to nighttime low help promote condensation within the equipment. Several times a year fog forms which provides additional opportunity for condensation problems. All the equipment associated with the SNBPSS, including the substation equipment, is specified to operate in a temperature range from 20°F to 120°F. Outdoor equipment is specified to operate properly when fully exposed to the sun and in rain and fog. The MFTF project's seismic guidelines require all vendors to confirm by calculations that their equipment will not cause a hazard during an earthquake. The switchgear is constructed in a standard outdoor non-shelter-aisle enclosure with gasketed doors. All other outdoor equipment is in NEMA 4 (water-tight and dust-tight) enclosures (where they are available) and all such enclosures are provided with space heaters.

Supporting Structures

The takeoff structure which deadends the PG & E 230-kV line is designed for a slack span at 1000 lbs tension. PG & E's requirements were for a minimum of 16 feet clearance from conductor to conductor. The lightning arresters and insulators are supported on steel columns. DMJM performed seismic analysis of all these structures to ensure that they conform with MFTF requirements.

Grounding

The grounding system for the substation is a fairly conventional grid with ground rods at frequent intervals. The specifications for the substation required a ground resistance no higher than 1 ohm. DMJM's calculations showed that this would be nearly impossible to realize in practice because of the very high soil resistivity at the Livermore site, especially during summer when the interval between rains may be seven or eight months. After the substation is in place, the grounding system will be tested (including measurement of the resistance to distant ground) to evaluate its performance and to check for hazards.

Personnel Safety Codes and Standards

The substation is being designed in accordance with the applicable California electrical codes and building standards and also in accordance with the applicable industry standards from ANSI, NEMA, and IEEE.

Fire safety precautions include the oil sumps mentioned above and hydrants at the perimeter of the substation. For safe nighttime access, the substation will be illuminated to an intensity of two footcandles over the entire area.

The substation yard is covered with four inches of crushed rock to limit step and touch voltage, and to provide a walking surface with low-conductivity for personnel safety. Oil sumps consisting of a 4-inch layer of large-diameter crushed rock are provided under each of the 60 MVA transformers. In the event of a transformer tank rupture, the oil sumps will prevent the oil from spreading and the crushed rock will cool and extinguish any oil fire. Each of these sumps can contain the entire quantity of oil stored in one transformer. An area at the western end of the substation, (reserved for another transformer and switchgear assembly which may be added later) will not have crushed rock. The grounding system will be continued through the area only enough to tie it to the adjacent accel dc-power-supply site-grounding system.

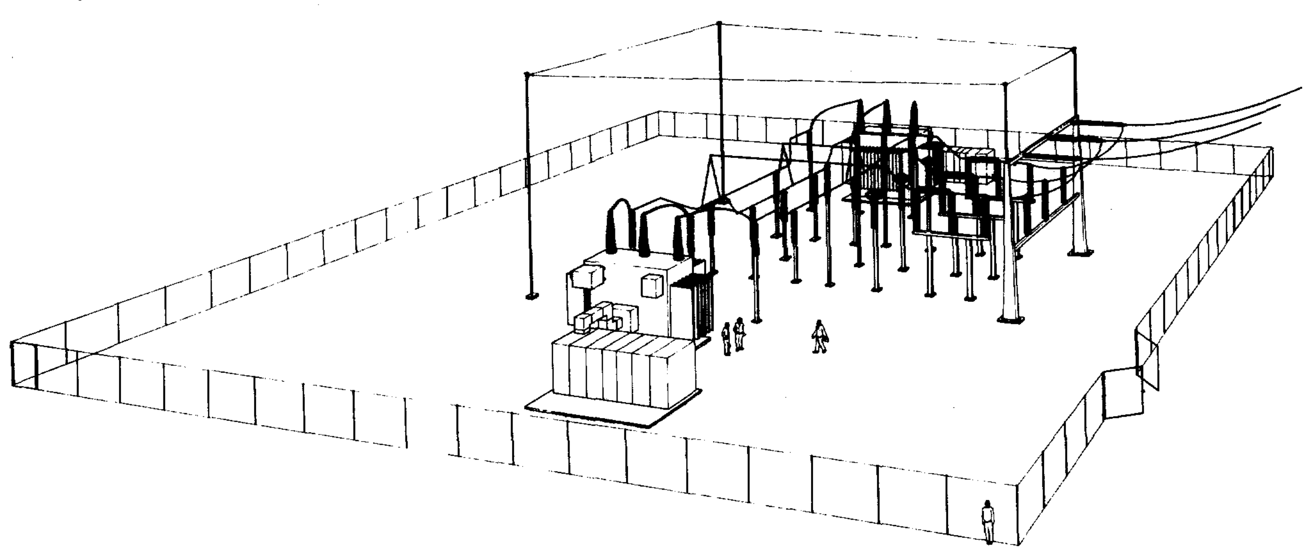

Fig. 6 Physical arrangement of the 230-kV Pulsed Power Substation